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Operational Performance of Sensor Systems Used to Determine Atmospheric Boundary Layer Properties as Part of the NASA Aircraft Vortex Spacing System Project

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1.0 Introduction

The National Aeronautics and Space Administration (NASA) is addressing the problem of capacity at our major airports through its Terminal Area Productivity (TAP) Program. The major goal of TAP is to provide the technology base and systems to permit the same airport capacity levels during instrument operations that are presently achieved during visual airport operations. A major initiative under TAP at the NASA Langley Research Center (LaRC) was the development of an Aircraft Vortex Spacing System (AVOSS) (Refs. 1, 2, 3, and 4). The purpose of AVOSS was to integrate current and predicted weather conditions, wake vortex transport and decay knowledge, and wake vortex sensor data to produce a dynamic wake vortex separation capability. By considering ambient weather conditions it is possible that aircraft separation distances can be safely reduced during appropriate periods of airport operation.

Numerous efforts were included as part of the AVOSS development program. Some of these were (1) understanding the complex interactions that occur among aircraft wake vortices, the atmospheric boundary layer, and the ground; (2) computational fluid dynamic (CFD) modeling of atmospheric boundary layer interactions with aircraft wakes; (3) developing operational algorithms to predict wake motion and decay; (4) developing and testing operational wake vortex sensors; and (5) establishing field facilities necessary for AVOSS testing and demonstration. A crucial component for these elements of the program was the measurement and collection of a substantial database of atmospheric boundary layer observations. Data needed for scientific investigations were of higher spatial and temporal resolution than that needed and used for AVOSS development, testing, and demonstration.

NASA LaRC initiated a multi-year field program with MIT Lincoln Laboratory to develop and deploy field systems to acquire high-quality atmospheric and wake vortex data. Major field activities included data collections from Memphis International Airport in 1994 and 1995, and at the Dallas-Fort Worth Airport in 1997, 1999, and 2000. An extended period of sensor operations during 1998 and into 1999 afforded a unique opportunity to determine important characteristics such as sensor robustness (unattended, continuous operation time) and representativeness (subjective determination of the validity of the output). In most cases it was easier to determine when the sensors were not producing realistic results than to infer anything about absolute accuracy due to the absence of ground truth.

As with any field measurement program, there are capabilities and limitations that must be understood in order to use the data most effectively as well as to learn and improve capabilities in the future. The field measurement programs permitted the comparison of sensors and systems measuring the same variable at nearly the same time and place, and to augment the understanding of sensor performance in an operational environment. The purpose of this report is to describe the sensor systems and settings used in more detail than in the past, to document limitations and how they might affect AVOSS, and to make recommendations as to optimal sensor combinations for AVOSS-type applications in the National Airspace System of the future.

2.0 Sensor Systems

Several insitu sensors and remote sensor technologies for atmospheric boundary layer measurements were employed at Memphis International Airport in 1994 and 1995 as well as at the Dallas-Fort Worth Airport from about June 1997 to July 2000. Included were Doppler sodars, a UHF profiler, Doppler lidars for limited periods, instrumented towers, radiometers, sonic anemometers, soil moisture and temperature sensors, precipitation sensors, and a line of anemometers. The complement of sensor data available also included the FAA Low-Level Wind Shear Alerting System (LLWAS), Terminal Doppler Weather Radars (TDWRs), radiosondes, and surface weather observations. Sensor systems will be described for each of the two locations.

2.1 Memphis

At the Memphis airport the following complement of sensors operated for limited periods: Two Doppler sodars manufactured by AeroVironment, Inc., a UHF Doppler profiler with Radio Acoustic Sounding System (RASS) option from Radian Corporation, a 45 m instrumented tower with wind and temperature sensors at 5 levels and fluxpaks consisting of high-frequency (10 samples per second) sonic anemometers at the top and bottom, two soil temperature probes, special radiosonde launches, and a radiometer. Also, an instrumented NASA aircraft was used in the 1995 deployment. An MIT Lincoln Laboratory Continuous Wave (CW) lidar was used to track and quantify aircraft wakes and runway cross-wind components. Table 1 lists pertinent characteristics of wind, temperature, and turbulence sensor systems (excluding aircraft) along with the data they produce. The accuracies listed are nominal values claimed by the manufacturer. In operational use less absolute accuracy would be expected from profilers, RASS and sodars depending on atmospheric conditions, siting, parameter settings, interference sources, and altitude. A discussion of sensor system behavior during limited periods of inter-comparisons in 1995 is available in the report Vigyan-2, Documentation of Sensor Accuracy, Limitations, and Quality Assurance Criteria Used in the 1995 Deployment, which is available on the Memphis compact disc (CD) (ref. 5).

2.2 Dallas-Fort Worth

Two meteorological towers (versus one at Memphis) were used at Dallas and up to five sites were used to simultaneously collect meteorological data from balloons (1997 only). There were two lidars and a wind line available to track and measure vortices and atmospheric winds at DFW: An MIT Lincoln Laboratory CW lidar, a NASA pulsed lidar, and a windline installed and operated by the John A. Volpe National Transportation Systems Center (ref. 6). Volpe also provided data from an AeroVironment M-3000/4000 minisodar in 1997. Only the CW lidar was used at Memphis. Two Remtech PA-2 sodars were used at DFW at two separate locations on the airport and the same 915 MHz atmospheric boundary layer profiler with RASS option that was used at Memphis was used at the Dallas-Fort Worth Airport. MIT Lincoln Laboratory also provided processed Terminal Doppler Weather Radar (TDWR) wind data from the DAL TDWR and DFW TDWR. Table 2 lists key features of wind, temperature, and turbulence sensors at DFW. More detailed discussions of sensor performance during the two Dallas deployment periods are in the Documentation subdirectories on the two DFW CDs (refs. 7, 8, and 9).

Those data have proven valuable for improving understanding of wake-atmosphere-ground interaction, for initialization and verification of mesoscale and cloud scale planetary boundary layer and wake behavior models, and for development and implementation of a demonstration AVOSS. The sensors employed in the AVOSS field deployments to date were compromises between the high resolution needs of scientific investigations and wake characterization, off-the-shelf operational (operate continuously, unattended) sensor systems available for immediate application, and remote systems that would not intrude into airport airspace or interfere with critical aviation communications or operations. They also provided the opportunity for longer term monitoring and evaluation because the sensors were operated more or less continuously at DFW since the summer of 1997. This report will focus on wind, turbulence, and temperature profile sensors utilized in AVOSS.

3.0 AVOSS Data Input Requirements

The basic requirement at the start of the project was to measure those atmospheric elements expected to have the greatest effects on wake vortex behavior and that would provide the input needed for AVOSS algorithms. Those elements were assessed to be the vertical profiles of wind, and temperature and some measure of ambient atmospheric turbulence in the same volume of air occupied by wakes from landing aircraft. Since the vortex lifetime was on the order of 1-2 minutes or less and horizontal and vertical dimensions of wakes were on the order of tens of meters, it was anticipated that for scientific studies wind measurements near the glide slope would be needed every few minutes with a vertical resolution of about 10 meters and horizontal resolution sufficient to capture atmospheric features that might be affecting the wakes. The vertical domain needed to be at least 600 m. The complement of sensors deployed represented a compromise in cost and capability for available state-of-the-art-atmospheric profile sensors. Some of the sensor systems such as the aircraft platform used at Memphis and the simultaneous balloon measurements at Dallas, 1997, were for specific scientific purposes of sensor validation and model verification, respectively. Those and others such as the minisodar and lidars were also used to aid in understanding wake behavior in a variety of atmospheric conditions and to confirm the influence of atmospheric variables during the AVOSS development process.

General meteorological input data required for latter stages of AVOSS algorithms are given in References 3 and 10. Those parameters and their primary and secondary effects are shown in Table 3 (see ref. 3). For lateral transport the cross-wind profile is primary with stratification (temperature profile-stability) and turbulence secondary; for vertical transport atmospheric variables of turbulence, cross-wind shear, and stratification are secondary effects; and for decay, turbulence has a primary effect with stratification secondary. "Thermals" can be considered a form of turbulence in large time and space domains. Upward speeds in thermals can exceed several m/s even as low as 100 m above the ground (ref. 11). Also important are non-atmospheric factors such as aircraft variables and ground effects for both transport and decay. The most recent version of AVOSS, AVOSS-2, used measured profiles of wind, temperature, and turbulence (eddy dissipation rate) from the surface to 600-m altitude described in more detail below (ref. 4). Observations were used to represent short-period (30-minute) forecasts and to provide validation data for specially-tuned mesoscale forecast models (ref. 12). The intent was not to predict characteristics of an individual wake, but to characterize the envelope of behavior so as to always include the worst-case from a potential vortex encounter perspective. Therefore, 30 minute averages and variances were used. Thirty minutes was a compromise between long-period statistics needed for spatial extrapolation and system stability together with the desire to compare wake predictions with observations of wake behavior from lidars dedicated to that purpose (ref. 3). Cross-wind profiles were measured by several sensor systems, but there can be considerable variability near the surface. Under some conditions a 1 m/s difference in cross wind can mean an increase of 12% in throughput defined as the percent increase in the maximum possible runway arrival rate resulting from use of AVOSS spacing relative to FAA-defined spacing criteria independent of cross winds (ref. 13). Also, with current sensors, excluding lidars, wind shear changes reported to affect vortex sinking in numerical studies (ref. 14) may not be resolved in sufficient vertical resolution. Turbulence profiles needed to provide estimation of vortex decay and for transport were the most difficult to measure. There were direct measuring sonic anemometers at just two levels on instrumented towers. Temperature profiles are also needed for assessing buoyancy effects on vortices descending behind the generating aircraft, but recent numerical studies have shown that stratification had little effect on vortex linking time, mean vortex separation, or vortex rising (ref. 15). For very strong inversions vortices stopped descending, but quickly dissipated.

The approach for AVOSS-2, that a specification based on observations of a mean condition together with a variance would be sufficient, is based on assumptions that the statistics of the mean variables are more or less representative of conditions expected at the wake locations; and also, that this representation would be valid for the next 30 minutes. The former assumption was tested for winds at 9-m height at the Shuttle Landing Facility, Kennedy Space Center (ref. 16). Although the statistics were different at times, even for spacings as close as 100 m, there was a useful relation found via normalized structure functions for known means and variances of winds at separate locations. For AVOSS-1 the variance of the wind was approximated by RMS spread among sensors measuring the same parameter such as winds or temperature and by time changes during the DFW field experiment in 1997 and through 1998 in a post-processing mode. Here, temperature profiles were based on curve-fit algorithms applied to RASS and tower data. Turbulence in the form of $\sqrt{2 \times TKE}$, an approximation to the combined wind component standard deviation, was used at one altitude in the early AVOSS code. Another approach was adopted for the AVOSS-2 tests completed in December 1999 when real-time profiles of turbulence and temperature became available. Wind variances were computed from tower observations over 30 minute averaging periods. These variances were assumed constant with altitude from the top of the tower (40m) to the top of the envelope of interest, 600m. Turbulence profiles were also available in Nov-Dec 1999. Eddy dissipation rate (EDR) and turbulent kinetic energy (TKE) were derived from tower fluxpak measurements and assumptions of boundary layer behavior described below. Reasonable results were produced by AVOSS using the half-hour average profiles and their variances (ref. 4). Mesoscale model forecasts of the three meteorological profiles were also available in 1999 as the first phase of a true small-scale dynamic model capability for the future.

The three required observation profiles and their meteorological input variables are discussed next.

3.1 Wind profiles

Wind profile specification is difficult because of the many heterogeneities and factors that influence near surface winds at any location and because each sensor measured the horizontal wind at different altitude and spatial resolution and in different averaging periods (see Table 2). MIT Lincoln Laboratory assembled wind profiles for AVOSS-2 from a variety of wind profile sensor inputs (refs. 17 and 18). The capability is called the AVOSS Winds Analysis System (AWAS). Runway cross-wind components and headwind components were analyzed from half-hour averages of sensor inputs. Sensors used in 1997-1999 were tower anemometers, profiler, the two sodars, and two Terminal Doppler Weather Radars (TDWRs). MIT Lincoln Laboratory also processed the later into vertical-point profiles in 50-m altitude bins every 5 minutes (ref. 19). The wind profile process evolved since 1995 to produce consistently good results as long as there is at least one good sensor measurement.

3.2 Turbulence profiles

The airport environments where turbulence data are needed prohibit tall towers and fixed structures on which to mount insitu turbulence sensors such as sonic anemometers. An approach taken for AVOSS-2 was the development by N.C. State University of an eddy dissipation specification based on tower sonic anemometer measurements, and wind speeds and temperatures from 3 and 10 meter levels coupled with Monin-Obukhov similarity theory (ref. 20). Eddy dissipation rates were calculated by MIT Lincoln Laboratory from wind spectra computed from sonic anemometers at 5 and 40 m. EDR profiles computed from Similarity algorithms had to pass through the computed EDR values at 5 and 40 m. Details of the process are given in Reference 21. The results have only been available for a few months and there is no basis for comparisons above the tower, but results appear consistent with expectations for near neutral and unstable conditions. During the early morning between about 0600 and 1100 UTC, when the atmosphere can be very stable, there can be a de-coupling of layers above the surface so that near surface measurements will not adequately represent conditions above the tower in clear, calm conditions under similarity theory.

3.3 Temperature profiles

AVOSS is least sensitive to temperature profiles (ref. 15) in a direct fashion although temperature profiles strongly influence turbulence and winds have more significant influences on vortex behavior (ref. 14). The greatest impact should come from strong inversions and changes near the surface where remote sensors such as RASS do not provide the vertical resolution to determine details of inversion structure below 100 m or even above 100 m in resolutions of 50 m or greater for research use. Temperature profiles adequate for AVOSS were assembled from tower measurements at 3, 10, 20, 30, and 43 m and from RASS measurements at 9 levels between 120 and 600 m. A polynomial curve-fit routine was employed to produce a single temperature profile at 50-meter intervals from 0 to 600 m every half-hour. This technique, coupled with input data quality assessments and corrections, worked well during the six months of testing, but problems with the lowest two RASS range gates created non-representative neutral lapse rates during the nocturnal inversion.

4.0 Sensor System Limitations

From the above discussion it is apparent that the tower anemometers, profiler, north and south sodars and TDWR sensors provide the inputs for vertical wind profiles. The tower and RASS provide the temperatures needed by the temperature curve-fit algorithms. Finally, wind speeds at 3 and 10 meters levels on the tower and virtual potential temperatures at these levels as well as calculated EDR at 5 and 40 meters provide the initial conditions for the turbulence profile algorithms. The focus in the following paragraphs will be on these sensors and especially remote sensing sodars, profiler, RASS, and TDWRs and their capabilities and limitations to support the prototype as well as future evolutions of an AVOSS. A high level summary of capabilities and limitations of remote sensor systems for wind and temperature profiles is shown in Table 4 and in Reference 22. The percentage of time that these sensors reported values at their respective times and altitudes is summarized in Tables 5 and 6. More details follow.

4.1 Doppler sodars

AVOSS has had experience with the AeroVironment M-2000, M-3000, 4000 (minisodars) and Remtech PA-2 phased array sodars. Table 7 lists detailed parameter settings for AeroVironment sodars, and Table 8 lists those for Remtech PA-2's. Their principles of operation are discussed in a number of recent publications (refs. 22, 23, 24, 25, and 26). Briefly, pulsed audio signals are directed along tilted radial channels, and the returned signal reflected by thermal turbulence is processed according to its observed Doppler shift into horizontal winds in range gates depending on internal parameter settings. This class of remote sensors has proven to be useful for a variety of atmospheric boundary layer measurements (ref. 27) and have been used for boundary layer wind measurements in the air pollution arena for about 30 years; but their limitations as operational sensors can be significant. Most of the comments and all examples are with the Remtech PA-2 sensors since these have been in operation the longest period of time. Sodars need an acoustically quiet environment free of buildings and other obstacles to be most effective. Airport environments are, in general, not quiet; so it is not surprising that the useful altitude range is limited much of the time to under 400 m for the Remtech PA-2s, even though they were set to produce data to 600 m. A 2000 Hz RASS operated near one of two sodar sites for 5 minutes of each 30-minute period. It caused additional noise problems for the north sodar also operating near the same frequency. Those problems were propagated subtly through all time periods in the case of the PA-2, but were most significant for the M-2000 just during the 5-minute times of RASS operation. The M-2000 was operated at several frequencies between 1497 Hz to 3000 Hz to minimize RASS interference. Remtech installed new software in September 1998 to reduce RASS interference problems in the PA-2 nearest to the RASS, since its frequency is fixed at near 2100 Hz. The software was effective but resulted in time averages of winds beyond that set by the operational parameters. The result was to delay real wind changes associated with fronts by 20 minutes or more. The sodar at the other location on the DFW airport was not affected by RASS interference. Strong winds blow the sodar signal out of the receiver's range when speeds exceed about 15 m/s, and surface winds of about 10 m/s can cause surface noise that interferes with signal processing as well. Effects of strong winds can be seen in the missing wind vector plots of Figure 1 for the north sodar on January 12, 1999. Altitude is shown on the y-axis and time of day (UTC) on the x-axis. Subtract 6 hours for Central Standard Time. During the period from 1700 to 2100 UTC (1100 to 1500L), surface winds exceeded 15 m/s and winds at 500 m were 20 m/s. Strong winds affected sodar performance on portions of 20 days in the period Jan 1998 – Jan 99 inclusive. Rain of moderate or greater intensity causes noise and other problems so that performance deteriorates. Heavy rain occurred between 0130 and 0330 UTC on February 22, 1998 and during this time the south sodar did not report many winds (Figure 2). Rain caused incorrect winds on portions of at least 27 days during 1998. Hail can damage the hardware unless a hail shield is used. Even though there are heaters, snow and freezing rain caused some loss of signal strength and performance degradation. Figure 3 shows the erratic behavior of the south sodar during an ice/snow/sleet storm on 27 January 2000 all afternoon.

There are other factors affecting sodar performance, which are not as obvious as ice, strong winds, and heavy rain. Strong inversions as occur on most clear mornings reduce the signal to noise ratios (S/N) and limit altitude coverage and general accuracy. Usually, the winds appear reasonable but are significantly weak above 200 m when compared to other sensors (Profiler, TDWR, aircraft). There is less S/N in cold weather and low humidity than in warm, humid air. Light wind conditions seem to produce more spurious returned signals and questionable wind solutions than steady flows. The horizontal winds in the first few range (altitude) gates have been usually stronger than those measured by nearby towers, probably due to the integration over finite range bins extending higher in altitude than the output altitude and non linearity of wind speed with altitude. It cannot be assumed that all winds are valid at all altitudes and times even when the weather is clear. There are incorrect solutions on some days and for some altitudes with no obvious cause (Figure 4). Some of the problems can be minimized by careful scrutiny of the S/N and other parameters listed in each output file.

Automated quality control criteria have been routinely applied to these wind sensors after-the-fact by NASA LaRC (ref. 9) and in real-time by MIT Lincoln Laboratory (ref. 18) with some success when used independently as well as in conjunction with other wind profile sensors.

There have been many wind events properly measured by these sensors, and they provide important input for an AVOSS-type application. One is afternoon eddies through the entire boundary layer. Figures 5 (a, b) is just one of many examples. Note that the wind direction changes in both sodars between 1400 and 1730 UTC (0900 to 1230L). Eddies were confirmed by the tower and the surface weather observation during this time. Low level wind maximum (called the low-level jet by meteorologists) signatures sometimes appear in sodar data, but their altitudes may be too low and strength underestimated. Figure 6 is a plot of all available wind sensors at 1130 UTC on 3 February, 2000. Note that the sodars show a maximum wind speed of 15 m/s at 200-m altitude that tapers off to 12 m/s at 400 m. Winds were available (Table 9) from ACARS (ARINC Communications, Addressing and Reporting System) (ref. 28), for an aircraft that landed at DFW at 1122 UTC and from the UHF Profiler at about the same time. They both indicate wind speeds of 18 m/s at a maximum altitude of about 400-m. Outflow boundaries from convective storms also appear in sodar data. The other remote sensors to be discussed smooth many of these features due to their coarser time and space resolution.

A Remtech PA-2 was operated for several weeks at Wallops Island VA when first received in early 1997 in cooperation with the NASA Wallops Flight Facility. This was a quiet environment, and accurate winds were produced to 600 m at 5-minute averages and 20 m vertical resolution. Comparisons were made with tethered balloon winds and an instrumented 100-m tower within 1.5 km of the sodar site. Sea breeze wind changes were also apparent in the data.

Experience with the minisodars was limited to a few months of comparisons. Their high time resolution (1 minute) and fine-scale altitude resolution (5 m) are offset somewhat by their limited maximum altitude of 200 m. Nevertheless, they produce details in the flow not available from other sensors. These sensors at DFW were positioned near the runway approach glide slope where aircraft and their wakes seemed to "contaminate" the wind data at times.

The sodars offer an attractive cost-capability tradeoff despite their problems in some conditions. A typical sodar cost is under $45,000. Minisodar cost is about $20,000. The PA-2 has been a reliable sensor system in terms of operation time as indicated by the statistics in Table 5.

4.2 UHF Profiler

A Radian Corporation Lap 3000 915 MHz lower atmospheric profiler was used in the field at Memphis airport in 1994 -1995 and at DFW airport since the summer of 1997. Wind Profilers detect minute fluctuations in atmospheric density, which are caused by the turbulent mixing of volumes of air with slightly different temperature and moisture content. Processing of the returned Doppler signals along tilted radials lead to horizontal and vertical wind solutions (refs. 25, 29, and 30). Profiler technology has been around for more than 30 years, and there are profiler networks in routine operation by the National Oceanographic and Atmospheric Administration (NOAA) with wind data available on-line at http://www-dd.fsl.noaa.gov/online.html. These network sensors, however, are tuned for high power, high altitude coverage. They typically operate at 404 MHz in 1 hour averages from 500 m to 16 km. The NASA Lap 3000 was operated at 25 minute averages in the region from about 100 m to 3400 m above the ground. At times during 1997 through 1999 the profiler was operated in dual-mode, alternating short pulse and long pulse. In short pulse, the lowest altitude was 110 m and the highest was 1979 m in 60 m vertical intervals. But the short pulse mode at times had erroneous winds in the lowest several range gates and did not seem to offer any real increase in vertical resolution. The Lap-3000 operated reliably over an extended period of time (Table 5) but, like the sodars, was subject to degradation due to precipitation and other conditions. Detailed parameter settings for the profiler and RASS in 1996, 1997, 1998 and 1999 are shown in Table 10. Acoustic noise was not a problem. Strong inversions attenuate the profiler signal and the lowest range gates are sometimes affected by sensitivity time controls used to attenuate strong signals nearest the transmitter. Profilers are more sensitive to precipitation than are sodars. Even light to moderate rain can affect performance. Figure 7(a, b) shows profiler and sodar wind vectors, respectively, during light to moderate rain on 21 Feb 1998. The rain occurred between about 1730 and 0000 UTC. Sodars were not affected by the precipitation at this time. Any objects, such as flocks of birds or aircraft, in the radar beams (tilted radials) can adversely affect performance. There were cases of profiler degraded performance during some afternoons. These may have been associated with interference, low S/N, or with reflection from taxiing, landing, and departing aircraft. Even though 915 MHz profilers at the Air Force Eastern Range have been operated successfully during the past five years at 10 minute averages, the NASA Profiler, when configured to operate at 15 minute averages in 1997, did not work well because there seemed to be too much interference. Parameter settings for NASA 15-minute averages are also shown in Table 10. Humid, hot environments produce more scatterers (and therefore stronger returned signal strengths) than dry, cold air. Atmospheric turbulence also produces more returned signals, but strong winds near the surface can increase clutter signals as well. A wind of 11 m/s along any radial component will produce a velocity fold and incorrect wind vectors. For a 23.5 degree tilt, the horizontal wind component would have to exceed 27 m/s in the profiler range before a velocity fold would occur.

Boundary Layer Profilers cost about $185,000, and they produce reliable and consistently good results. The trade-off is cost, lower altitude resolution, and longer averaging periods. Low-level wind maxima were most faithfully captured by the profiler.

4.3 RASS

The Radian RASS generated acoustic signals around 2000 Hz that were channeled into the radar vertical beam. Enhanced scattering of the radar occurs at specific frequencies (Bragg scattering). The resultant Doppler shift and speed of sound can be determined. That speed is directly related to the atmospheric virtual temperature, the temperature of dry air if its pressure and density were the same as the moist air. Usually virtual temperature is 2-3 degrees C higher than dry-bulb temperature measured in the summers at Dallas and Memphis. In cold dry air there is little difference between the two. RASS was configured to produce temperatures every 60 m between 120 and 1492 m, but useful range was limited to 600 m. Cold temperatures significantly reduced altitude coverage in the winter to about 300 m. The first two range gates (120 and 180 m) were frequently corrupted by ground clutter especially when vertical motion correction was applied. In 1998, as shown in Table 6, there were 82% of the measurements available at the 120-m level and less than 50% above 540 m. In the winter season (Dec., Jan., Feb., and Mar.) there were only 70 % available at 120 m and 40 % above 540 m. It was determined not to use the corrected temperatures in 1999 because of this problem, but uncorrected temperatures could be off by 2 degrees during actively convective (thermals produced) afternoons. Uncorrected temperatures can introduce unreal thermal oscillations in the 200 – 400 m altitude range on sunny afternoons. Vertical motion of 1 m/s can change the temperature by 1.6 degrees K. Rain of even light intensity adversely affects RASS temperatures and, like for the sodars, strong winds can blow the acoustic signal out of the radar beam. Strong inversions generally lowered altitude coverage in late night and early morning. Techniques were developed to deal with many of these problems during real-time thermal profile generation. Those are briefly discussed in the Documentation folder on the DFW 99 CD (ref. 8). The cost of a RASS option with a profiler is $32,200. RASS options are also available with sodars at a cost of about $44,000. The RASS option with the sodar has not been tested.

4.4 TDWRs

These radars were developed and installed as part of a FAA program at 41 major airports for the specific purpose of detecting microburst-type wind shears. In the Dallas-Fort Worth area there were two TDWRs, DAL and DFW. The TDWRs were separated by about 15 km, the closest (DAL) 5 km east of the north end of the airport runways and the farthest (DFW), 20 km to the NE. Through special processing at MIT Lincoln Laboratory, vertical wind profiles were created to best represent the winds over the DFW airport (refs. 17 and 19). Although using frequent update rates of 5 minutes and 50-m vertical altitude bins, these radars covered a larger geographic area than the other sensors. That most likely accounted for the 3-4 times per year when TDWR winds were different from those indicated by the other sensors over the airport. One example is shown in Figures 8 and 9. On the morning of October 14, 1999, there was an east-west stationery front just north of the airport with north winds north of the front, and south to southwest winds to the south. The DFW TDWR (Figure 8) was indicating a northwest wind below 200 m between 0730 and 1200 UTC while the other sensors (Figure 9) were showing south winds. In Figure 9 all sensors reporting winds at 0800 UTC are plotted in their respective symbols and in meteorological components (for U-component West to East flow is positive; V-component North to South flow is positive). Cold, dry air significantly reduced scatterers, so that in winter, winds were rarely available above 200 m; and there were extended times when no valid solutions were available until late afternoon. In Table 5 the low average percentages for either TDWR (47% for DAL and 52% for DFW) was the result of missing data in the winter when there were not enough scatterers in the atmosphere for the

Doppler processor to reach a wind solution. Like the radar profiler, TDWRs were also adversely affected by inversions and low ambient turbulence. One important strength of TDWRs was their enhanced performance in precipitation when the sodars and profiler do not work well. TDWRs can complement other sensors and provide important input for the wind profile process (ref.17, 18).

4.5 Lidars

Pulsed or continuous wave (CW) lidars were operated only during the field deployments to Memphis and Dallas-Fort Worth airports. During times when not used for wake detection and tracking, lidars measured the winds in their field of view. The lidars were not tuned for atmospheric wind profile measurements and required significant manual interaction. The lidar operated by MIT Lincoln Laboratory at all deployments was a 10.2 micron CW lidar. Technical characteristics are discussed in Reference 17. Briefly, the lidar collected backscattered laser radiation near the ends of the runway. The Doppler shift of the backscattered radiation from atmospheric particulates was converted to velocity along the measured azimuth. By scanning in the vertical plane oriented perpendicular to the extended runway center line, adjusting the focus range of the laser transmitter, and combining the atmospheric returns with a reference laser beam, vertical profiles of the horizontal wind (cross-wind at DFW) were obtained. In wind mode, the lidar scanned at 180 degrees per second. Range resolution was 6 m at 100-m distance, but varied with the square of the distance. Time averages of 1 minute were used and considerable smoothing at the higher altitudes took place. Resulting cross-winds were 1 minute averages in 10 meter vertical bins up to a maximum of 400 m. NASA operated a 2.02 micron pulsed coherent lidar manufactured by Coherent Technologies, Inc. Its technical characteristics are discussed in Reference 31. The same principles as above apply except that ranging was accomplished by pulse tracking. At Dallas the range resolution was 30 m, and the lidar produced crosswind profiles up to about 100-m altitude with vertical resolution 0.5 m near the surface and about 1 m at 100 m. This lidar could rotate in azimuth so that the wind vector profile could also be obtained when it was dedicated to wind profile measurements. Lidars, in general, also have some difficulties in heavy precipitation as well as dense fogs and low clouds. A Lidar configured for wind and turbulence profile measurements would cost about $250,000. Lidars offer an attractive alternative for AVOSS despite their cost if they will be needed to provide confirmation of actual vortex behavior and if the same lidar can be configured to produce turbulence profiles as well as wind profiles.

4.6 Fluxpaks (turbulence sensors)

Two sonic anemometers were configured to measure the three velocity components and temperature at ten samples per second. All variances and cross-correlations were output each minute. The averaging period used was 30 minutes for AVOSS-2. From wind spectra eddy dissipation rate can be derived. Turbulent Kinetic Energy was computed directly from the three component variances. They only provide measurements at a point. During the field deployments there was one at 5 meters and one at 40 meters on the south tower. The sensors were adversely affected by precipitation and fog. During precipitation, it is possible to use only the horizontal cross-correlations for turbulence calculations; and during fog, turbulence is usually very low. Fluxpaks typically cost $12,000-15,000 each.

4.7 Savpaks

Temperature and wind were measured on the tower at 5 levels using standard propeller-vane anemometers and R. M. Young temperature-humidity probes. Those sensors were very reliable. The low percentages of availability in Table 5 are due to an extended communications outage caused by damaged cables. Lightning also damaged some of these sensors. Savpak sensors cost about $15,000 each. The biggest expense is the tower installation. The 45-meter tower used in the past cost about $30,000, but site preparation, electrical, etc can cost up to $500,000, depending on locale. A 30-m tower could suffice with Savpaks at 3, 15, and 30 m and Fluxpaks at 5 and 30 m.

5.0 Conclusions and Recommendations

Many of the sensor performance issues discussed above are most likely the result of the adverse environment, a busy airport, where these sensors had to operate. Despite shortfalls at times, there were a great majority of times when valid data were obtained. Quality assurance procedures, algorithms, and criteria were applied in both real-time and after-the-fact with considerable success to produce the profiles of winds, temperature, and turbulence used by AVOSS for testing and demonstration. All sensors providing input to AVOSS have been discussed above. Recommendations that follow are predicated on the continued need for these three profiles in future AVOSS applications.

The cost-effective measurement of temperature and wind at two levels near the ground needs to continue in order to use the turbulence profile algorithms until other sensors (profilers, lidars, sodars) demonstrate the capability. The two levels should be at about 3 and 10 m above the ground. For temperature profile generation, direct measurements of temperatures need to be available to as high an altitude as possible in order to provide accurate ground truth and to anchor the merging of temperatures with remote sensors such as RASS above the tower. Pressure is needed at one level near the ground for virtual temperature calculation and use with RASS measurements. A 45-m tower is expensive to install and might not be allowed at all airports. Such a tower, though, would provide an adequate direct measurement of turbulence for use to anchor the turbulence profile algorithms. A shorter tower (say 30 m) could suffice at many locations to provide a reasonable direct measure of turbulence. There are towers at most major terminals that house the LLWAS sensors. These may serve also as cost-effective platforms for savpak and fluxpak sensors. Turbulence algorithms could also benefit from a measurement of atmospheric boundary layer height that can be derived from sodars. In the future it is possible that the profiler can be configured to produce a useful measure of atmospheric turbulence profiles as well as winds. A profiler also provides the validation capability for numerical weather models and initial conditions most closely suited to weather model input and output needs.

Since the profiler was the most consistent and reliable source of atmospheric wind profiles, it is recommended as the sensor of choice (with RASS option) even though its cost is higher than that of the sodars and its time and space resolution are lower. Second choice would be a sodar-RASS combination. A lidar dedicated to wind and turbulence profile measurements is an alternative in all weather except dense fog, moderate precipitation, and low clouds. During fog, ambient turbulence and cross winds are usually low so the resultant spacing saving potential for AVOSS is low (ref. 10). Table 10 summarizes these options.

Lidars were not used as AVOSS wind sensors except for a few brief periods. It is well known, however, that lidars are capable wind sensors (Ref. 32) outside of clouds, fog, and precipitation and can produce wind-field statistics (ref. 33).

In summary, the most cost-effective complement of sensors for near-term AVOSS application are the following: (1) small tower (existing LLWAS, if possible) on which three Savpak sensor systems (measuring temperature, and winds at three levels) as well as two fluxpaks, one at the top and one at the bottom, measuring temperature and wind component fluctuations from which eddy dissipation and TKE can be derived; (2) UHF Profiler with RASS for wind and temperature profiles; and (3) Lidar for wind and turbulence profiles as well as wake vortex detection. If costs allow, a sodar would complement the profiler and lidar and provide somewhat better performance in precipitation. At ITWS locations, continue to make TDWR winds available to a wind merging capability. The TDWRs work well in the rain.

A near-term capability can also be to combine short-period forecasts with observations so as to preserve the trends in the time change from model dynamics but adjust or correct the forecast for the current time using the current observations. Finally, ACARS (aircraft) wind, temperature, and turbulence observations in the runway approach corridor can be a viable option in the next few years.

There will never be perfect sensors. The challenge is to understand and mitigate their limitations, and exploit their capabilities in any operational use scenarios.

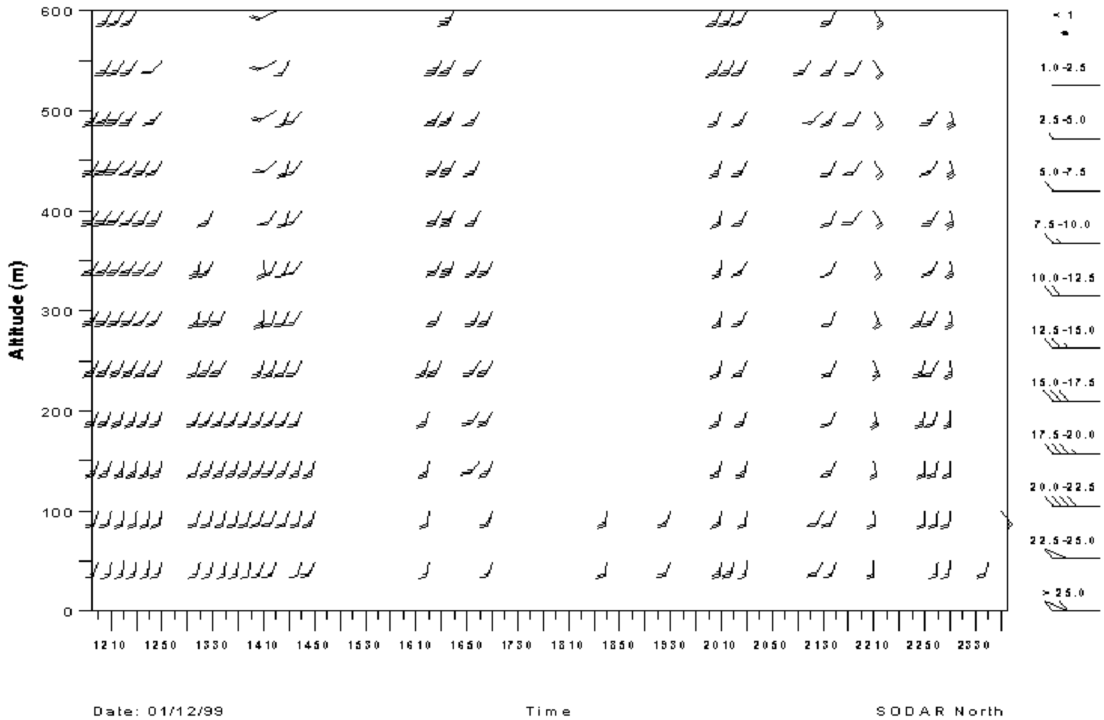


Figure 1: Wind vectors from the North Sodar at DFW on January 12, 1999 illustrating strong wind effects.

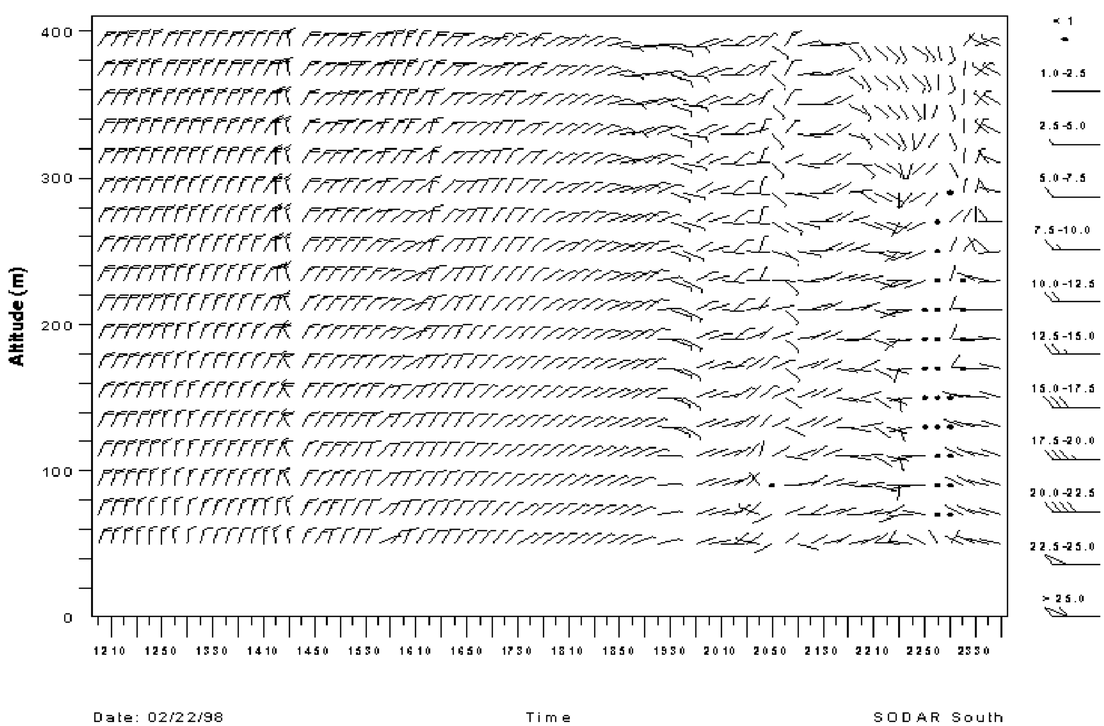


Figure 2: Wind vectors from the South Sodar at DFW on February 22, 1998 during heavy rain.

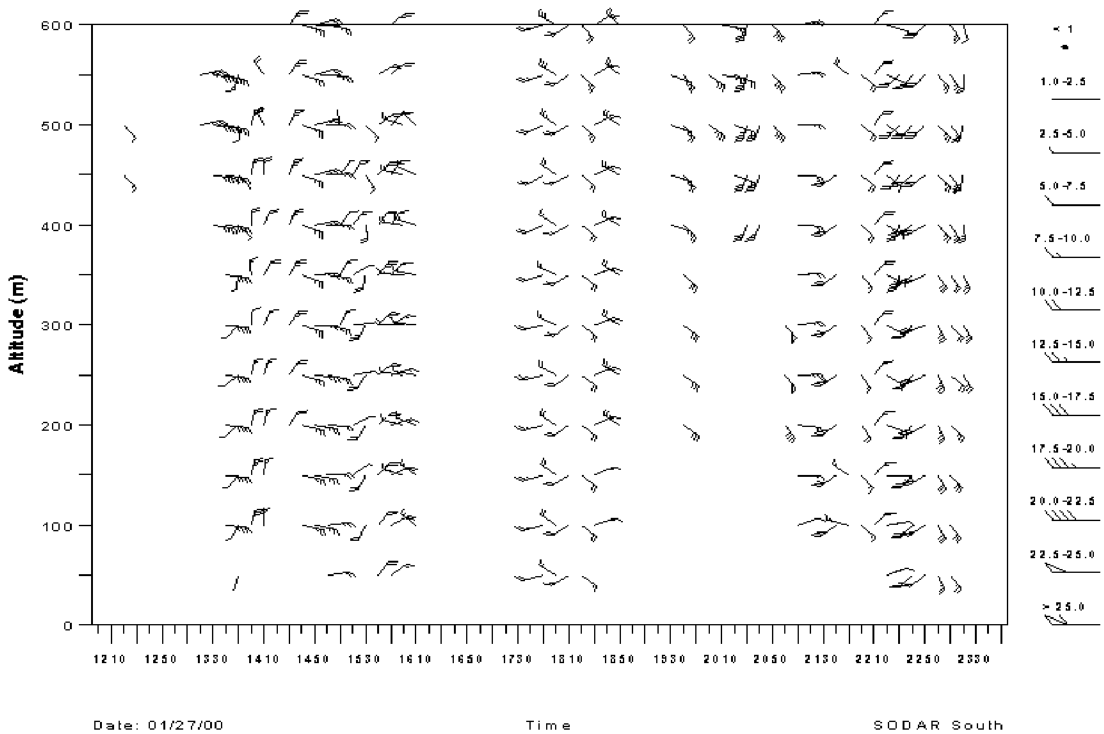


Figure 3: Ice, snow and freezing rain effects on Sodar performance at DFW on January 27, 2000.

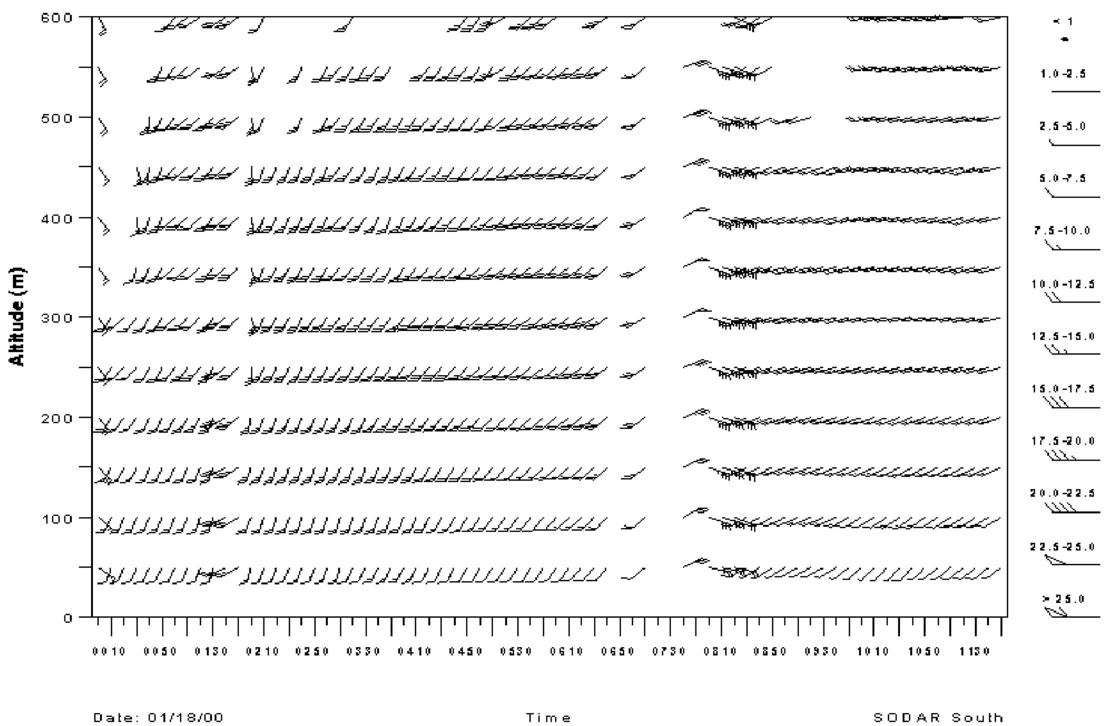
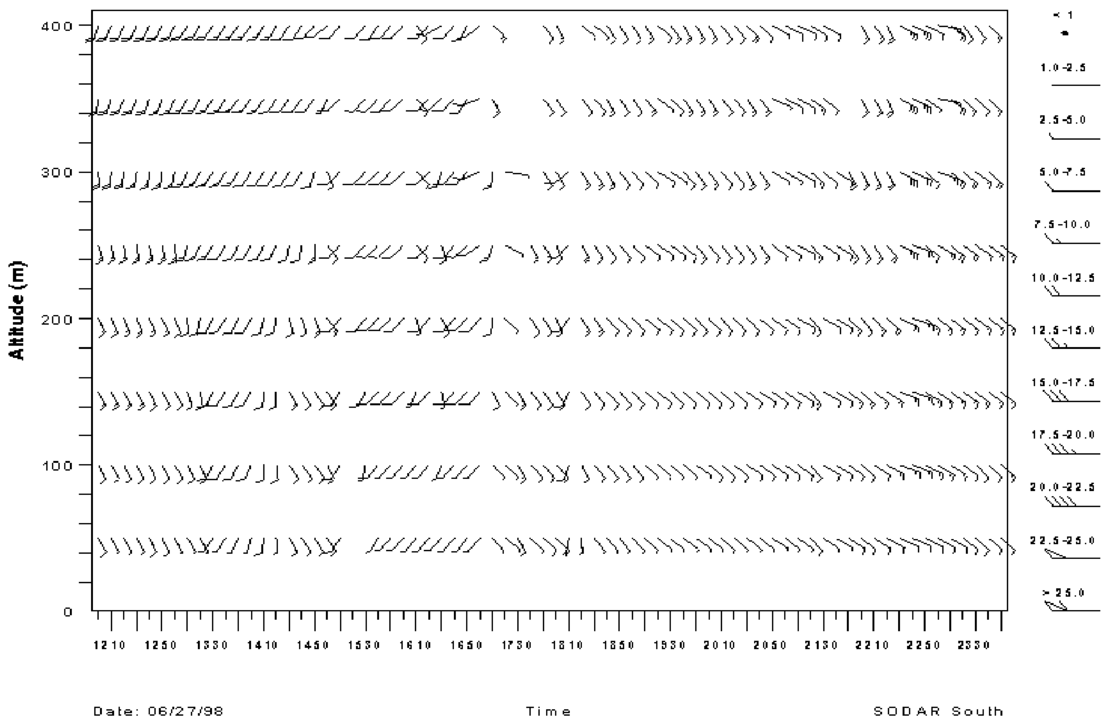
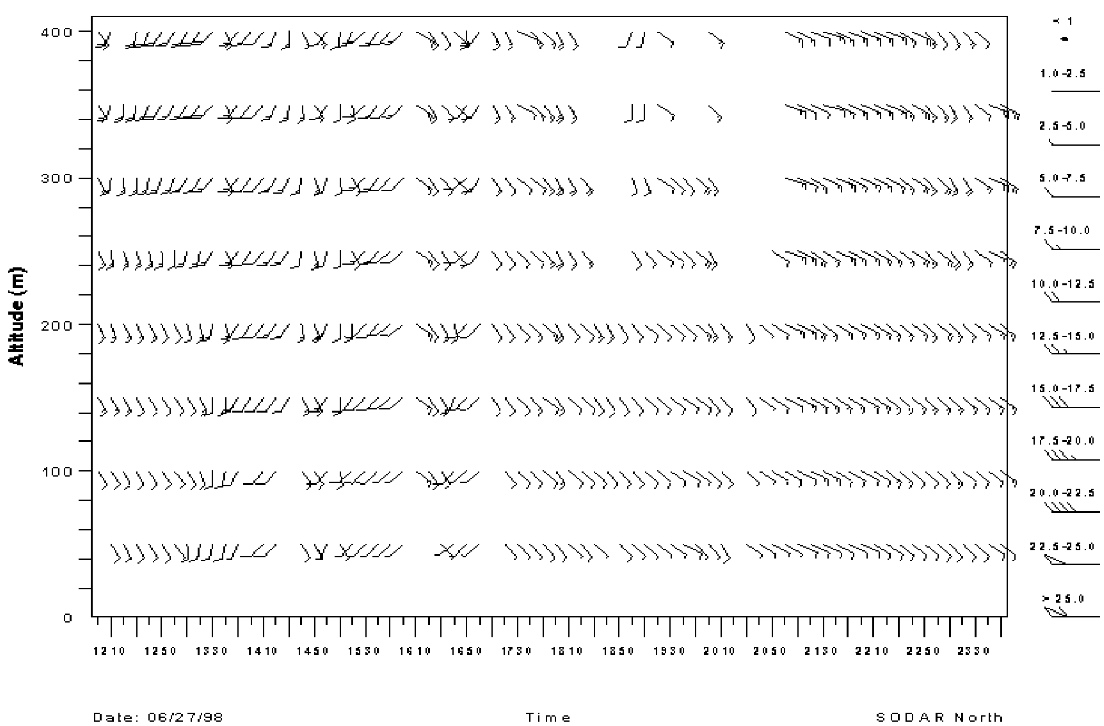


Figure 4: South Sodar wind vectors during good weather at DFW on January 18, 2000.



5a: South Sodar June 27, 1998.



5b: North Sodar June 27, 1998.

Figure 5: Sodar wind vectors at DFW with eddies causing wind direction changes.

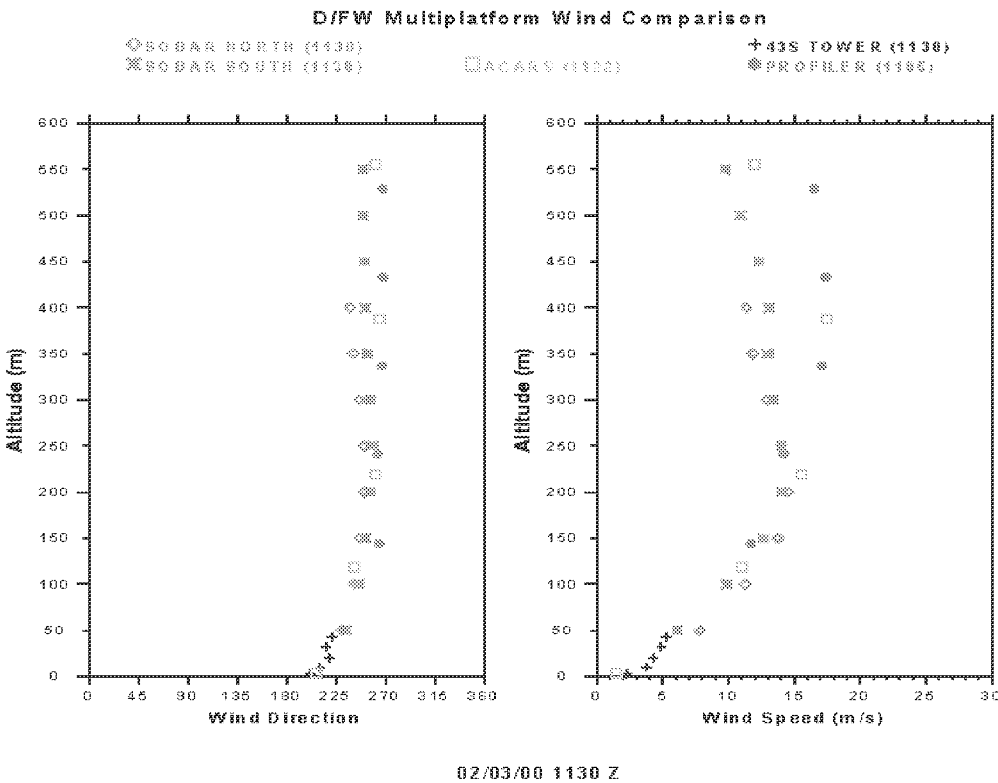
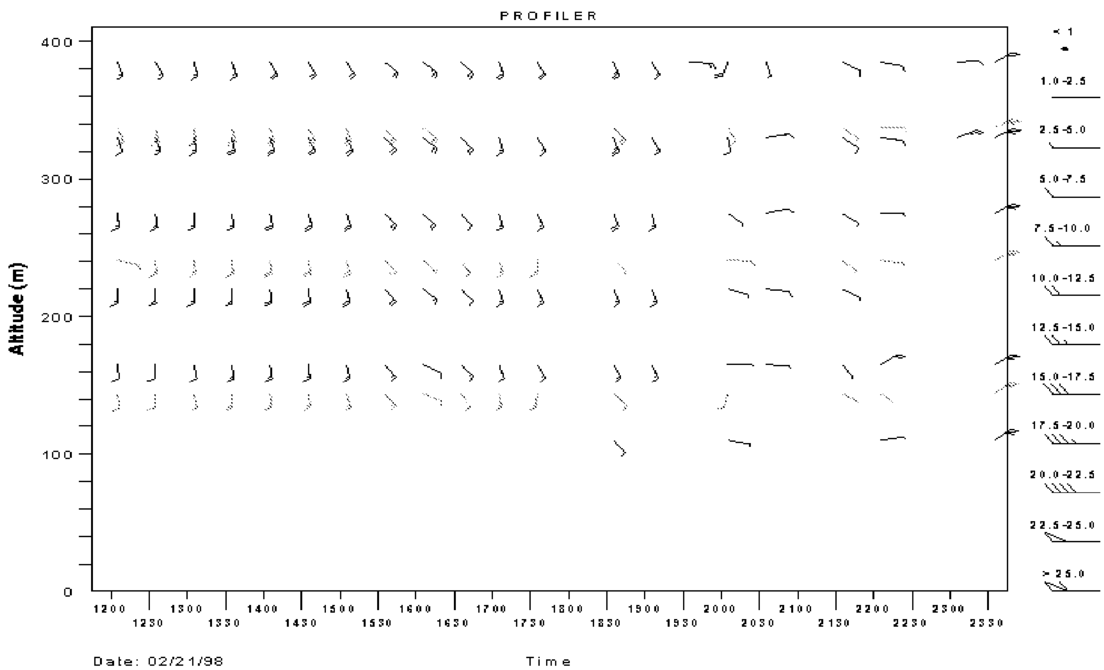
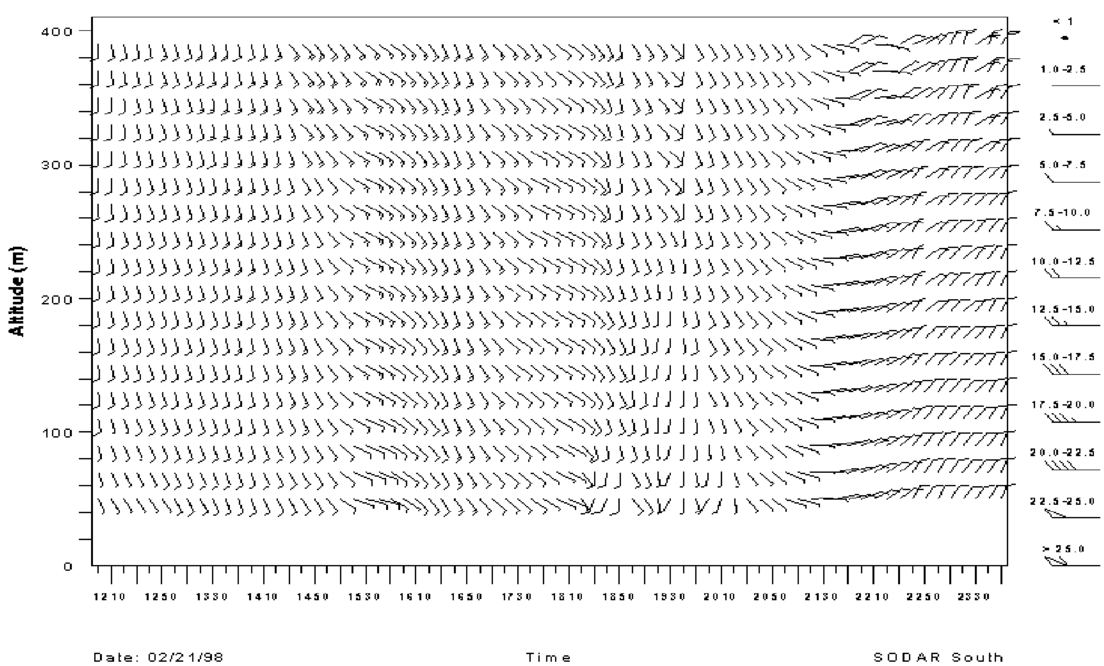


Figure 6: Wind direction and speed vs. altitude as measured by sodars, towers, profiler, and a landing aircraft on February 3, 2000 at DFW.



7a: Boundary layer profiler wind vectors in rain.



7b: South Sodar wind vectors.

Figure 7: Remote sensor wind profiles at DFW in rain on February 21, 1998.

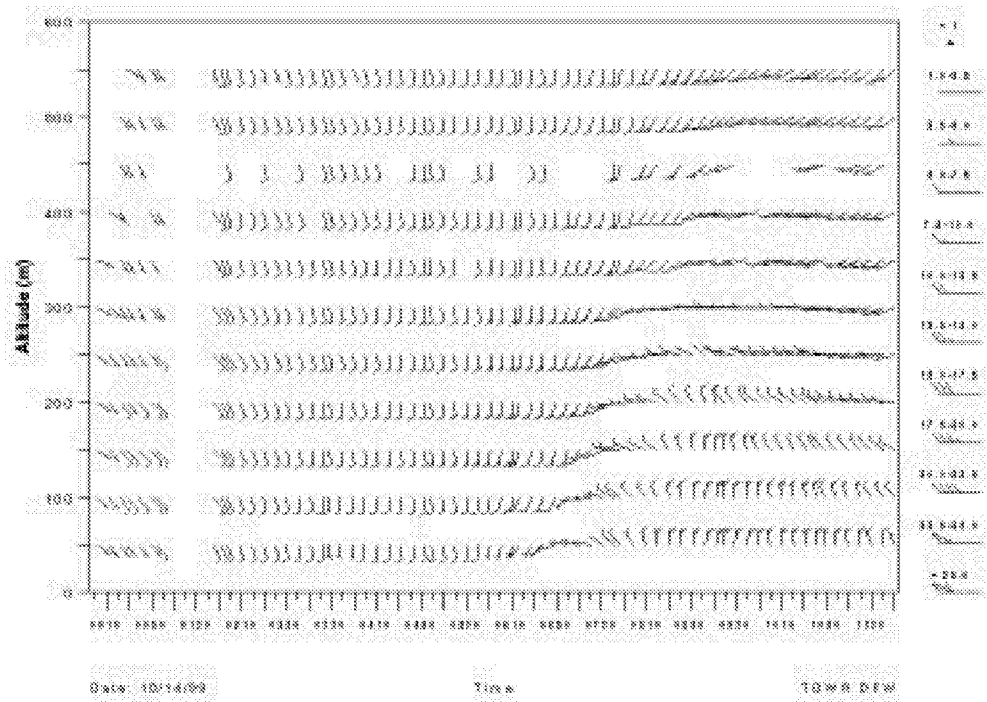


Figure 8: DFW TDWR wind vectors 0000 to 2350 UTC on October 14, 1999.

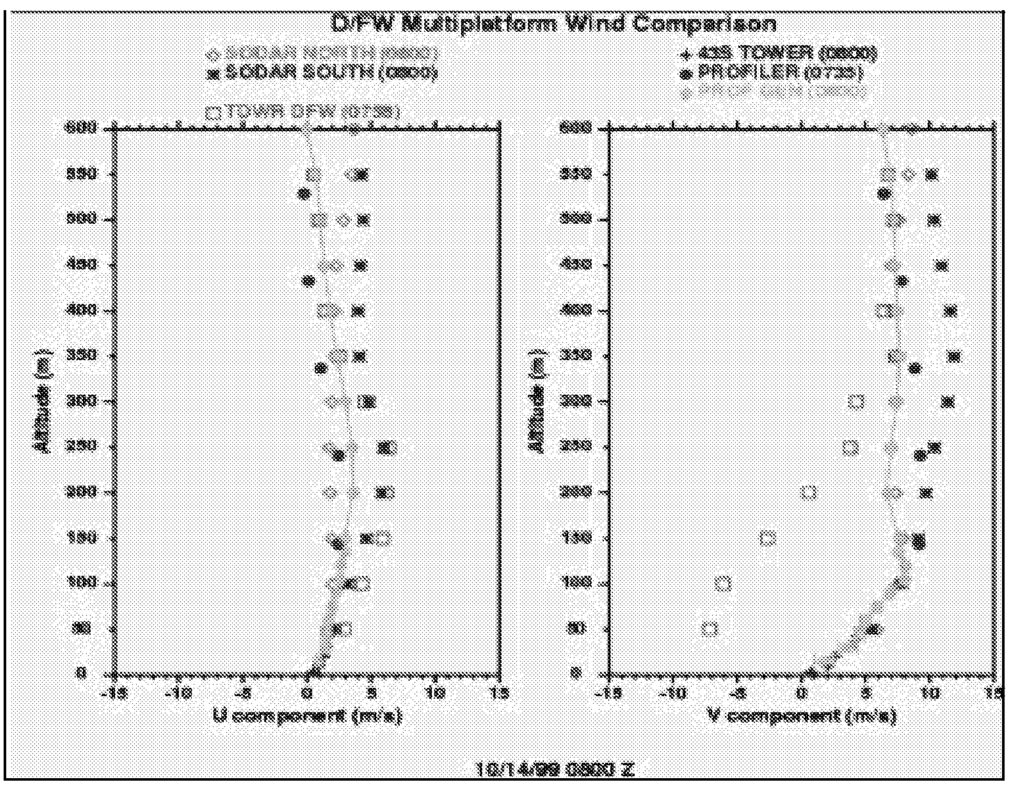


Figure 9: Multiplatform wind component plots for 0800 UTC on October 14, 1999.

Table 1: Characteristics of Atmospheric Boundary Layer Sensors Used at Memphis International Airport

Sensor System	Sensor Type	Manufacturer	Parameter Output	Averaging Period	Freq./Output Rate	Horizontal Resolution	Vertical Resolution	Altitude Range	Accuracy
Tower SAVPAK	Temp- Rel. Hum.	R.M.Young 41372C	Temperature (T)	1 min	1 Hz/ 1 min	Point	5, 10, 20, 30, 42 m	5-42 m	0.3C
	Temp- Rel. Hum.	R.M.Young 41372C	Relative Humidity	1 min	1 Hz/ 1 min	Point	5, 10, 20, 30, 42 m	5-42 m	3 percent
	Prop Vane Anemom.	R.M. Young AQ05305	Wind Direction (dd)	1 min	1 Hz/ 1 min	Point	5, 10, 20, 30, 42 m	5-42 m	1 deg
	Prop Vane Anemom.	R.M. Young AQ05305	Wind Speed (vv)	1 min	1 Hz/ 1 min	Point	5, 10, 20, 30, 42 m	5-42 m	2 percent
	Aneroid Barometer	Vaisala PTA427	Atmospheric Pressure (P)	1 min	1 Hz/ 1 min	Point	2 m	0 m	0.15 mb
Tower FLUXPAK	Sonic Anemometer	Applied Technologies	Virtual Temperature (Tv)	1 min	10 Hz/ 1 min	Point	5, 40 m	5, 40 m	0.05C
	Sonic Anemometer	Applied Technologies	East Wind Component (u)	1 min	10 Hz/ 1 min	Point	5, 40 m	5, 40 m	0.05 m/s
	Sonic Anemometer	Applied Technologies	North Wind Component (v)	1 min	10 Hz/ 1 min	Point	5, 40 m	5, 40 m	0.05 m/s
	Sonic Anemometer	Applied Technologies	Vertical Wind Component (w)	1 min	10 Hz/ 1 min	Point	5, 40 m	5, 40 m	0.05 m/s
	(computed)	Applied Technologies	Temperature Variance (T`)	1, 5, 15 minutes	1 min	Point	5, 40 m	5, 40 m	
	(computed)	Applied Technologies	East Wind Variance (u`)	1, 5, 15 minutes	1 min	Point	5, 40 m	5, 40 m	
	(computed)	Applied Technologies	North Wind Variance (v`)	1, 5, 15 minutes	1 min	Point	5, 40 m	5, 40 m	
	(computed)	Applied Technologies	Vertical Wind Variance (w`)	1, 5, 15 minutes	1 min	Point	5, 40 m	5, 40 m	
	(computed)	Applied Technologies	Covariances of above	1, 5, 15 minutes	1 min	Point	5, 40 m	5, 40 m	
UHF Profiler	Pulse Doppler Radar	Radian Corp.Lap3000	Wind Speed (VV) computed	25 min	25 min/ 30 min	215 m at 300 m Altitude	97 m	145 - 4881m	1.0 m/s
			Wind Direction (dd) computed	25 min	25 min/ 30 min	215 m at 300 m Altitude	97 m	145 - 4881m	10 deg
			Vertical speed	25 min	25 min/ 30 min	215 m at 300 m Altitude	97 m	145 - 4881m	

Table 1 (continued)

Sensor System	Sensor Type	Manufacturer	Parameter Output	Averaging Period	Freq./Output Rate	Horizontal Resolution	Vertical Resolution	Altitude Range	Accuracy
RASS	Echosonde	Radian Corp.	Tv (computed)	5 min	5 min/ 30 min	Vertical (overhead)	95-96 m	127 - 1492m	1 C
Sodar	Doppler Accoustic Sounder	AeroVironment INC M-2000	Horiz. Wind Speed (computed)	10 min	10 min/10 min	Vertical (overhead)	20 m	20 - 400m	0.2 m/s
			Horiz. Wind Dir. (computed)	10 min	10 min/10 min	Vertical (overhead)	20 m	20 - 400m	10 deg
			Vertical Speed (computed	10 min	10 min/10 min	Vertical (overhead)	20 m	20 - 400m	5 cm/s
MiniSodar	Doppler Accoustic Sounder	AeroVironment INC M-4000	Horiz. Wind Speed (computed)	1 min	1 min/1 min	Vertical (overhead)	5 m	5-200 m	0.2 m/s
			Horiz. Wind Dir. (computed)	1 min	1 min/1 min	Vertical (overhead)	5 m	5-200 m	10 deg
			Vertical Speed (computed	1 min	1 min/1 min	Vertical (overhead)	5 m	5-200 m	5 cm/s

Table 2: Characteristics of Atmospheric Boundary Layer Sensors Used at Dallas-Fort Worth International Airport

Sensor System	Sensor Type	Manufacturer	Parameter Output	Averaging Period	Freq./Output Rate	Horizontal Resolution	Vertical Resolution	Altitude Range	Accuracy
Tower SAVPAKs	Temp- Rel. Hum.	R.M.Young 41372C	Temperature (T)	1 min	1 Hz/ 1 min	Point	5, 10, 20, 30, 44 m	5-44 m	0.3C
	Temp- Rel. Hum.	R.M.Young 41372C	Relative Humidity	1 min	1 Hz/ 1 min	Point	5, 10, 20, 30, 44 m	5-44 m	3 percent
	Prop Vane Anemom.	R.M. Young	Wind Direction (dd)	1 min	1 Hz/ 1 min	Point	5, 10, 20, 30, 44 m	5-44 m	3 deg
	Prop Vane Anemom.	R.M. Young	Wind Speed (vv)	1 min	1 Hz/ 1 min	Point	5, 10, 20, 30, 44 m	5-44 m	0.2m/s
	Aneroid Barometer	Vaisala	Atmospheric Pressure (P)	1 min	1 Hz/ 1 min	Point	2 m	0 m	0.15 mb

Table 2(continued)

Sensor System	**Sensor Type**	**Manufacturer**	**Parameter Output**	**Averaging Period**	**Freq./Output Rate**	**Horizontal Resolution**	**Vertical Resolution**	**Altitude Range**	**Accuracy**
Tower FLUXPAKs	Sonic	Applied Technologies	Virtual Temperature (Tv)	1 min	10 Hz/ 1 min	Point	5, 40 m	5, 40 m	0.05C
	Krypton Hygrometer	Applied Technologies	Mixing Ratio	1 min	20 Hz/ 1 min	Point	5 m	5, 40 m	0.5 g/m3
	Sonic Anemometer	Applied Technologies	East Wind Component (u)	1 min	10 Hz/ 1 min	Point	5, 40 m	5, 40 m	0.05 m/s
	Sonic Anemometer	Applied Technologies	North Wind Component (v)	1 min	10 Hz/ 1 min	Point	5, 40 m	5, 40 m	0.05 m/s
	Sonic Anemometer	Applied Technologies	Vertical Wind Component (w)	1 min	10 Hz/ 1 min	Point	5, 40 m	5, 40 m	0.05 m/s
	(computed)	Applied Technologies	Temperature Variance (T`)	1, 5, 15 minutes	1 min	Point	5, 40 m	5, 40 m	
	(computed)	Applied Technologies	Specific Humidity Variance (q`)	1, 5, 15 minutes	1 min	Point	5, 40 m	5, 40 m	
	(computed)	Applied Technologies	East Wind Variance (u`)	1, 5, 15 minutes	1 min	Point	5, 40 m	5, 40 m	
	(computed)	Applied Technologies	North Wind Variance (v`)	1, 5, 15 minutes	1 min	Point	5, 40 m	5, 40 m	
	(computed)	Applied Technologies	Vertical Wind Variance (w`)	1, 5, 15 minutes	1 min	Point	5, 40 m	5, 40 m	
	(computed)	Applied Technologies	Covariances of above	1, 5, 15 minutes	1 min	Point	5, 40 m	5, 40 m	
UHF Profiler	Pulsed Doppler Radar	Radian Corp.Lap3000	Wind Speed (VV) computed	25 min	25 min/ 30 min	215 m at 300 m Altitude	100 m	145 – 4881m	1.0 m/s
			Wind Direction (dd) computed	25 min	25 min/ 30 min	215 m at 300 m Altitude	100 m	145 – 4881m	10 deg
			Vertical speed	25 min	25 min/ 30 min	215 m at 300 m Altitude	100 m	145 – 4881m	
			Signal/ Noise	25 min	25 min/ 30 min	215 m at 300 m Altitude	100 m	145 - 4881m	
RASS	Echosonde	Radian Corp.	Tv (computed)	4 min	5 min/ 30 min	Vertical (overhead)	100 m	127 - 1492m	2 C

Table 2(continued)

Sensor System	**Sensor Type**	**Manufacturer**	**Parameter Output**	**Averaging Period**	**Freq./Output Rate**	**Horizontal Resolution**	**Vertical Resolution**	**Altitude Range**	**Accuracy**
SODAR	PA-2	Remtech	Horiz. Wind Speed (computed)	10 min	10 min/10 min	Vertical (overhead)	20 m	20 - 400m	0.2 m/s
			Horiz. Wind Dir. (computed)	10 min	10 min/10 min	Vertical (overhead)	20 m	20 - 400m	10 deg
			Vertical Speed (computed	10 min	10 min/10 min	Vertical (overhead)	20 m	20 - 400m	5 cm/s
			Structure Constant	10 min	10 min/10 min	Vertical (overhead)	20 m	20 - 400m	
			std. dev. of vert. wind (w`)	10 min	10 min/10 min	Vertical (overhead)	20 m	20 - 400m	
			std. dev. of horiz wind (u`,v`)	10 min	10 min/10 min	Vertical (overhead)	20 m	20 - 400m	

Table 3: Primary and Secondary Effects on Wake Behavior (after Hinton, Charnock, Bagwell, Griggsby, 1999)

Wake Factor	**First Order Influences**	**Second Order Influences**
Lateral Transport	Cross-wind profile Ground effect	Aircraft variables Stratification Turbulence
Vertical Transport	Aircraft variables Ground effect	Turbulence Stratification Cross-wind shear
Decay	Turbulence Ground effect	Aircraft parameters Stratification

Table 4: Summary of Capabilities and Limitations of Atmospheric Boundary Layer Remote Sensors

	Doppler Sodar (winds)	**Boundary Layer Radar Profiler (winds)**	**RASS (temperature)**	**Doppler Lidar (winds)**
STRENGTHS	• Continuous sampling of lower atmospheric boundary layer (ABL) • Smaller sample volumes (finer vertical resolution) • Smaller time integrations • (finer time resolution) • Responds to afternoon eddies, outflow boundaries, fronts • Can sample below 50 m • Relatively low cost	• Continuous sampling of ABL • Data recovery not as sensitive to high winds • Not sensitive to acoustic noise • Works better in turbulent atmospheres • Captures low level wind maxima in early mornings • Moderate cost	• Can produce several virtual temperature profiles per hour • Can work with profilers or sodars • Low to moderate cost	• Continuous sampling of ABL • High temporal and spatial resolution • Not sensitive to acoustic or EM noise • Responds to eddies, outflow boundaries, fronts
LIMITATIONS	• Altitude coverage limited during inversions • Interference from acoustic noise sources (like RASS) • Interference from precipitation • High (>15m/s) winds limit altitude coverage • Nuisance effects from unknown sources • Some incorrect winds are output with no obvious cause • Performance degrades in low humidities, cold	• Interference from precipitation • Interference from birds, aircraft • Lowest altitude sampled ~ 100 m • Larger sample volumes, coarser resolution • Ground clutter interference possible • Performance degrades in low humidities	• Adversely affected by precipitation • Altitude coverage limited during inversions • Output is virtual temperature, must convert to compare with dry-bulb temperatures • Nuisance effects from acoustic noise sources • Should correct for vertical motion • Interference from ground clutter in first two range bins (via vertical motion correction) • Altitude coverage limited in winter • There are some systematic error sources (~1deg K)	• Limited range in fog, clouds • Limited range in precipitation • Unattended operation needs more demonstration • Relatively high cost

Table 5: Percent of Data Received Jan 1998 through Jan 1999

Month	**AWAS**	**Profiler**	**N. Sodar**	**S. Sodar**	**43 m Tower savpak**	**43 m Tower fluxpak**	**DAL TDWR**	**DFW TDWR**
Jan 98	56	85	76	86	100	82	39	59
Feb	95	77	83	91	75	74	21	16
Mar	72	41	68	64	66	63	23	18
Apr	76	78	87	84	97	80	55	55
May	94	88	94	88	97	96	65	68
Jun	100	93	88	87	100	100	67	72
Jul	100	86	65	88	85	80	66	70
Aug	95	86	62	84	6	6	68	80
Sep	90	77	61	72	52	52	60	68
Oct	100	85	79	82	100	85	63	72
Nov	100	86	70	81	100	97	50	61
Dec	98	84	66	74	100	91	24	23
Jan 99	100	77	69	81	100	96	10	13
ALL	89	80	79	82	83	77	47	52

Table 6: Percent of reported observations by altitude and month for the DFW RASS during 1998

month	120 m	180 m	240 m	300 m	360 m	420 m	480 m	540 m	600 m	660 m	720 m	780 m	840 m	900 m	960 m
Jan	68%	92%	87%	80%	71%	61%	51%	43%	32%	24%	18%	14%	11%	10%	8%
Feb	77%	97%	96%	91%	79%	66%	55%	45%	34%	26%	21%	16%	11%	7%	5%
Mar	71%	88%	84%	76%	65%	56%	48%	41%	34%	24%	19%	14%	10%	8%	6%
Apr	92%	99%	98%	97%	92%	83%	75%	66%	56%	47%	36%	27%	21%	16%	11%
May	91%	99%	99%	99%	98%	96%	91%	84%	73%	63%	53%	46%	39%	32%	25%
Jun	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Jul	96%	99%	100%	99%	99%	97%	90%	81%	69%	59%	50%	43%	37%	31%	24%
Aug	96%	99%	99%	99%	98%	96%	89%	84%	79%	73%	66%	60%	54%	48%	43%
Sep	94%	100%	100%	99%	99%	98%	95%	87%	79%	72%	64%	56%	50%	44%	39%
Oct	92%	98%	99%	98%	98%	95%	86%	76%	63%	52%	41%	32%	27%	21%	17%
Nov	80%	99%	97%	96%	92%	86%	76%	64%	52%	40%	31%	25%	20%	16%	12%
Dec	66%	82%	81%	78%	69%	54%	42%	34%	25%	20%	15%	11%	8%	5%	3%
ALL	85%	96%	95%	93%	89%	83%	75%	67%	58%	50%	43%	37%	33%	28%	24%

Table 7: Parameter Settings for AeroVironment Sodars

	M-2000, processor-1	***M-2000, processor-2***	***M-3000, minisodar***	***M-4000, minisodar***
frequency	1497 Hz	2000-2300 Hz	2800 Hz	4500 Hz
averaging period	10-20 min	10 min	1 min	1 min
output interval	10-20 min	10 min	1 min	1 min
altitude range	60-600 m	40-500 m	30-??? m	15-200 m
altitude interval	30 m	30 m	20 m	5 m
number of beams	3	3	3	3
tilted radials zenith	20 Deg	20 Deg	20 Deg	16 deg
min amplitude for acceptance	N/A	15	15	Adaptive
FFT size	N/A	64	64	64
min signal to noise for acceptance	N/A	2	5	7
sodar pulse length	180 ms	180 ms	150 ms	50 ms
vertical correction	No	Yes	Yes	Yes
max # transmit pulses	30 / 60	60	6	15
sample rate	Analog Processed	960 Hz	960 Hz	960 Hz

Table 8: Parameter Settings for Remtech Sodars

Parameter	**Explanation**	**1997**	**1998**	**Sep-98**	**1999**
Software	version #	V6	V6.06	V7.05	V7.05
HMIN	min altitude (m)	50	50	50	50
DELTAH	altitude interval (m)	20	20	50	50
NSDAY	# of layers	30	30	12	12
STAT0	status of com-1	1	1	1	1
STAT1	status of com-2	0	0	0	0
PSTAT0	print status term-0	1	1	1	1
PSTAT1	print status term-1	0	0	0	0
MAXBLO	storage block size	2300	2300	2300	2300
SMATIM	averaging time (min)	5	5	10	10

Table 9: Aircraft Sounding (see text) from Descending Plane Landing at DFW at 1122 UTC on Feb 3, 2000.

P_alt (ft)	P (mb)	t/td (°C)	w_dir/w_spd (kts)	Bng/Rng from gnd pt (nm)	
390	999	7.3/-----	207°/003	283°/002	1122 UTC
770	985	9.3/-----	242°/022	316°/002	1122 UTC
1100	974	12.3/-----	261°/031	328°/004	1121 UTC
1650	954	11.8/-----	265°/035	339°/004	1121 UTC
2200	935	12.5/-----	261°/024	348°/007	1120 UTC
2520	924	12.3/-----	268°/025	8°/008	1119 UTC

Table 10: Parameter Settings for Radian Profiler and RASS

	PROFILER								RASS		
	MEM 1994-1995		DFW 1997		DFW 1997 (15min)		DFW 1998-1999		MEM 1995	DFW 1997	DFW 1998-1999
Parameter	short	long	short	long	short	long	short	long			
Interpulse Period (ns)	23	50	23	35	23	43	23	35	20	20	20
Pulse Width (ns)	400	700	400	700	400	700	400	700	700	400	400
Delay (ns)	1600	1900	1600	1900	1600	3300	1600	1900	1700	1600	1600
Spacing (ns)	400	700	400	700	400	1400	400	700	700	400	400
# Gate Heights	35	50	35	37	25	22	35	35	14	25	24
# Coherent Averages	350	160	350	212	340	180	324	212	10	10	10
# FFT Points	64	64	64	64	64	64	64	64	2048	2048	2048
# Spectral Averages	42	50	42	55	42	42	50	55	55	20	20
% Needed for Consensus	50	50	60	60	60	60	60	60	50	65	70

Table 11: Options for AVOSS Meteorological Sensors

Sensor	**Parameters**	**Cost**	**Limitations**
Fluxpak	Turbulence, temperature	\$15,000	Precipitation, fog, no profile
Savpak	Wind, temperature, humidity	\$15,000 (tower: ~\$500,000)	No profile
Profiler	Wind profiles	\$185,000	Precipitation, starts at ~100 m
RASS	Temperature profiles	\$32,200 w profiler \$44,000 w sodar	Precipitation, starts at ~100 m
Sodar	Wind profiles	\$46,000	Noise, inversions, strong winds
Lidar	Wind, turbulence profiles Wake behavior	\$500,000	Fog, clouds, precipitation
TDWR	Wind profiles	N/A	Cold, dry atmospheres; area average Only at selected locations

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13. ABSTRACT (Maximum 200 words)
There has been a renewed interest in the application of remote sensor technology to operational aviation and airport-related activities such as AVOSS. Radio Acoustic Sounding Systems (RASS), Doppler-acoustic sodars, UHF profilers and lidars have many advantages in measuring wind and temperature profiles in the lower atmospheric boundary layer since they can operate more or less continuously and unattended; however, there are limitations in their operational use at airports. For example, profilers deteriorate (limited altitude coverage or missing) in moderate or greater rain and can be affected by airplane targets in their field of view. Sodars can handle precipitation better but are affected by the high noise environments of airports and strong winds. Morning temperature inversions typically limit performance of RASS, sodars and profilers. Fog affects sonic anemometers. Lidars can have difficulties in clouds, fog or heavy precipitation. Despite their limitations these sensors have proven useful to provide wind and temperature profiles for AVOSS. Capabilities and limitations of these and other sensors used in the AVOSS program are discussed, parameter settings for the sensor systems are documented, and recommendations are made for the most cost-effective group of sensors for the future. The potential use of specially tuned dynamic forecast models and measurements from landing and departing aircraft are addressed.

14. SUBJECT TERMS
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